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Life cycle assessment of direct co-firing of torrefied and/or pelletised woody biomass with coal in The Netherlands

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ABSTRACT

In this paper the Life Cycle Assessment (LCA) is used to evaluate the environmental benefits on global warming, acidification and photochemical oxidation potentials, of biomass direct co-firing with coal on a 20% energy input basis, when compared with coal-fired power generation in The Netherlands. The solid biofuel is produced from Dutch or Canadian forestry biomass via pelletisation, torrefaction or torrefaction and pelletisation. The results show that torrefied biomass co-firing chain can be considered the best option when Dutch biomass is utilised. The reduction is approximately 12% for global warming, 7% for acidification and 5% concerning photochemical oxidation potentials. Even when biomass is imported from Canada, this also results in substantial reduction regarding global warming potential, when compared to the reference case. Alternatively, co-firing of domestic biomass results in a better performance than Canadian biomass for all three impact categories. Therefore, concerning global warming all the suggested resources for co-firing result in environmental benefits compared to coal-fired power generation.

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1. Introduction

Diminishing the usage of fossil fuels is one of the main tasks faced in the prevention of global warming and, to a further extent, climate change. In this regard the coal is a fuel with the highest environmental impact, as it is the largest CO_2-emitting fossil fuel in terms of weight per unit of energy produced. Therefore, on a European and on a national level there have been attempts with policies and drivers to reduce the use of coal, especially in electricity generation as approximately 43% of the emitted CO_2 is derived from electricity and heat production industry (IEA, 2012). One of the options to reduce coal utilisation in power generation is its partial or total replacement with biomass.

In this paper information regarding the Dutch political field corresponds to the year 2012. Dutch policy is strongly related to EU policy. The Dutch subsidy for biomass co-firing in coal-fired power plants ended (Sawin et al., 2012). However, the Dutch government made clear that its intention is mandating biomass co-firing in all power plants. The government discussed and agreed on a minimum of 10% of biomass input on weight basis (Gibson, 2011). On the other hand, power companies produce emissions that contribute to significant environmental impacts, such as global warming. Therefore, in planning new production capacities, the Dutch power companies will have to seek a more sustainable energy balance.

Life Cycle Assessment (LCA) is continuously getting more attention as it can help evaluate products and services and identify possible improvements. During the past decade there was a rapid increase in LCA studies (Guinée et al., 2011). Therefore, LCA is now considered a powerful tool with respect to sustainability. Additionally, concerning power generation, there have been LCA analyses of national electricity generation systems, combustion of coal, biomass co-firing with coal and single fuel biomass combustion. More specifically, Hartmann and Kaltschmitt (1999), Mann and Spath (2001), Tabata et al. (2011), Huang et al. (2013), Royo et al. (2012) and Fan et al. (2011) have all conducted LCA studies with respect to biomass co-firing with coal. Whereas, Damen and Faaij have performed a Life Cycle Inventory (LCI) on biomass import chains in The Netherlands (Damen and Faaij, 2003). All authors mentioned above either focused on global warming impact or on Greenhouse Gas (i.e. GHG) emission production. However, none of them has yet focused on a relative novel, high prospect technology such as torrefaction or torrefaction combined with pelletisation (TOP), of woody biomass. Finally, no LCA studies on direct co-firing of biomass with coal in the Dutch context have been conducted.

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Torrefaction is a promising technology, with potential to have a major impact to the commodification of biomass. Its considered added value is the production of a more coal-alike solid biofuel with higher energy density and better physical and combustion properties, which consumes substantially less energy to be palletized than fresh biomass. Additionally, this solid fuel has significant lower moisture content than fresh biomass, it is hydrophobic and more homogeneous. Torrefaction adds value in the logistics chain as well; torrefied and pelletised biomass is considered safer for transportation than conventional pellets, whereas cost savings are also expected (Bridgeman et al., 2008; Bagramov, 2010; Carter, 2012; Phanphanich and Mani, 2011; Patel et al., 2011; Shah et al., 2012).

Woody biomass in The Netherlands is mainly derived from four sources, such as forests, roadside, orchards and wood processing industry. In this paper woody biomass originates from forests and roadside. The Netherlands has 360,000 ha of forest, of which almost 25% has a protected area status. Furthermore, 55% of the available forest is harvested annually which corresponds to 1.2 Mtons of fresh wood (Probos, 2011). 70% of the available wood is used as round wood for industrial use, whereas the rest is used as residential firewood, energy pellets and small to medium scale bioenergy applications (Kuiper and Oldenburger, 2006). Wood pellets were the main form of biomass used in the Dutch power plants until 2010 and almost the only one imported for co-firing purposes (Goh et al., 2012).

Canada was selected to be the country to produce and deliver the alternative biomass source in this paper. Canada is the largest wood pellets exporter to The Netherlands and it is very rich in biomass resources, approximately 645 Mtons are harvested annually. As more than 60% of wood pellets are produced in British Columbia (Magelli et al., 2009), this region was selected for this analysis.

In this paper 55% of the available total annual increment of forestry biomass is harvested for co-firing purposes, as mentioned above regarding current Dutch practices, while the rest is left on site to avoid carbon stock depletion. However, this proportion can be further increased up to 80%, similar to sustainably managed forests in Europe.

There are several Dutch electricity companies which co-fire biomass with coal already. That said, wood pellets still are the dominant form of biomass used for co-firing purposes (Dutch Ministry of Economic Affairs, Agriculture and Innovation, 2010). Most of the co-firing power plants in The Netherlands are located in South-Holland or close to this province, and the port of Rotterdam is one of the largest globally and it already has a clear interest of becoming a bioenergy-hub. Therefore, the Rotterdam's area was selected as the most suitable area for location of the power plant in this paper. As a result it was decided that the pretreatment plants and the cement factory would be located close to the port, and approximately not more than 130 km away. Finally, the source of biomass was selected to be no further away than 200 km from the pretreatment plants. Both are average distances, which can be realistic as The Netherlands is a small country.

The aim of this paper is to evaluate the environmental benefits on global warming, acidification and photochemical oxidation potentials, of biomass direct co-firing with coal on a 20% energy input basis, when compared with coal-fired power generation in The Netherlands. LCA is used for this evaluation. The solid biofuel is produced from Dutch or Canadian forestry biomass via pelletisation, torrefaction or TOP. The results show that torrefied biomass co-firing chain can be considered the best option when Dutch biomass is utilised. The reduction is approximately 12% for global warming, 7% for acidification and 5% concerning photochemical oxidation potentials. Therefore, it is important to notice that the selected environmental impacts are associated with not only the co-firing stage, but also with the entire biomass supply chain.

2. Materials and methods

The CMLCA software, developed by Heijungs and Leiden University (Heijungs, 2009) and the CML and Traci models are used in this paper to acquire assessment results on the environmental impacts.

2.1. LCA methodology

2.1.1. Goal definition

The aim of this cradle-to-gate LCA study is the comparison and evaluation of benefits regarding selected impacts of pretreated biomass co-firing chains in The Netherlands, with respect to coal combustion for power generation. Additionally, identification of the most influential life cycle stages in the entire chain is pursued in order to suggest possible improvements or bottlenecks. Therefore, focus has been given on the whole biomass chain; from harvesting to transportation of the produced ashes to the cement production factory. Moreover, the use of waste resources was considered in this paper. As a result, waste woody biomass, derived from Dutch forest maintenance, has been selected as the biomass source, and the produced mixed ash from the power plant was used as feedstock in a cement production factory.

The choice of this comparison is made because the Dutch government considers making co-firing mandatory for Dutch power plants. Furthermore and as explained above, torrefaction is a very promising technology regarding bioenergy systems; and Rotterdam port is one of the largest globally, with an interest of becoming a bioenergy-hub. Finally, if the environmental benefits are not strongly influenced by transportation stage, this analysis can also be applied to other European countries, bigger than The Netherlands.

2.1.1.1. System boundaries. The cradle-to-gate system boundaries of a woody biomass supply chain for power generation are shown in Fig. 1. The biomass co-firing chains consist of several stages including: harvesting and chipping of the woody biomass on production-site, storage, transportation, pretreatment in order to produce a solid fuel, co-firing and, finally, transportation of the produced mixed ash to a cement production factory. Furthermore, the life cycle steps of the production chain of coal, such as mining, processing and transportation, were also taken into account in the boundaries. On the other hand, regarding the reference case the stages included are mining and processing of hard coal, transportation, combustion and, finally, transportation of the produced ash.

Consumption of materials and energy regarding the construction and demolition of relevant infrastructure are excluded from the system boundaries, as several studies have shown that their contribution is insignificant and negligible when compared with the fuel production or operational stages (Damen and Faaij, 2003; Hartmann and Kaltschmitt, 1999; Mann and Spath, 2001).

2.1.1.2. Functional unit. The selected function unit is 1 kWh of electricity produced by the power plant. The functional unit is used to compare the environmental impacts of the different pretreated biomass co-firing systems and reference system.

2.1.1.3. Allocation. Economic allocation is used in this paper in multifunctional processes to allocate material and/or energy consumption, and produced environmental emissions. A multifunctional process is a process which has more than one functional flow, i.e. flows that constitute the process goals. Economic allocation is

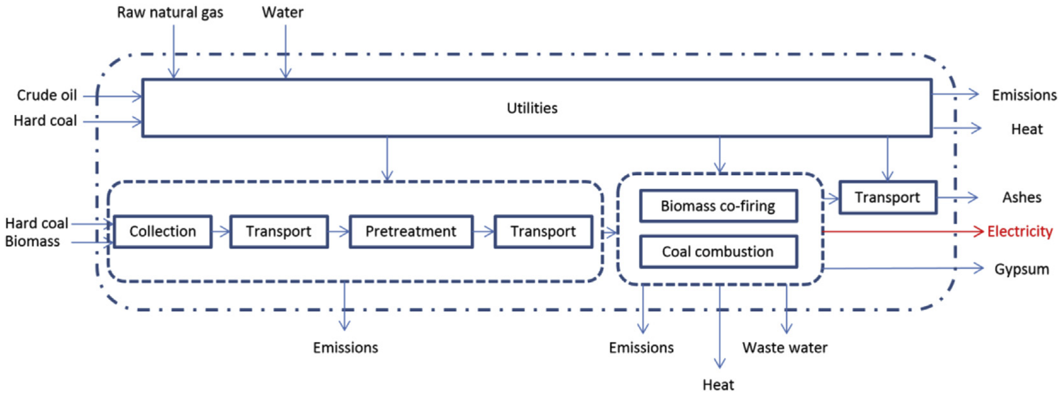

Fig. 1. System boundaries.

the partitioning of input and output of multifunctional processes based on their economic value and their produced amounts (Guinée et al., 2004). The allocation factors are presented in Table 1.

2.1.1.4. Study assumptions. This paper was focused on woody biomass produced and pretreated in The Netherlands or Canada and co-fired in South-Holland. Therefore, the power plant was decided to be located there, have the capacity of 500 MW_e and a net efficiency of 40%; similar to E.ON's Maasvlakte 1 power station. This means that 100 MW_e will have to derive from biomass feedstock. If the power plant already co-fires biomass with coal, then, for the case of power generation from coal only, an increase of the efficiency is expected. The utility boiler increase is of 1% for each 10% of coal replacing biomass on an energy basis (Canalis et al., 2005). Regarding wood pellets production, the pellet plant has a production capacity of 70 ktons/a (Junginger and Sikkema, 2009). Regarding torrefied wood and torrefied wood pellets the plant has a production capacity of 60 ktons/a. The pretreatment plants selected in Canada are both in the region where biomass is produced. The pellet plant and the torrefaction plant have production capacities of 53 ktons/a and 110 ktons/a (Koppejan et al., 2012), respectively. All the plants' capacities considered in this work have been based on capacities of actual plants in the region of northern Europe. Finally, with respect to the power plant, it is assumed that 97 and 98% of the carbon in the biofuels and coal, respectively, is fully combusted to CO_2; the rest ends up in the ashes. On the other hand nitrogen and sulphur contents of the fuels are combusted to SO_2 and NO_x, respectively.

2.2. Impact categories

The selection of the environmental impacts is based on their influence by energy and transport systems. That said, the selected impacts in this paper are global warming for 100 years, which is also known as carbon footprint, acidification and photochemical oxidation. Furthermore, the biogenic CO_2 which is emitted in the different LCA systems is presented only for comparison purposes. Global warming is selected in this paper, since it is the most significant environmental concern with respect to transport and energy systems. Furthermore, acidification and photochemical oxidation impact categories are selected as they both result in air pollution and, consequently, affect the local climate. Finally, acidification impact is also affected by transport and energy systems.

Table 1
Multifunctional processes and economic allocation.

Products	Lumber mill	Power plant
	Allocation factor	Allocation factor
Timber	0.4007	
Sawn logs	0.3887	
Sawdust	0.1111	
Chips	0.0304	
Bark	0.0691	
Electricity		0.989
Gypsum		0.011

2.3. Life Cycle Inventory

The different stages during the life cycles of the systems are described below. The data used are presented in Table 2, and they have been collected either from international literature or from the Ecoinvent database.

2.3.1. Harvesting of forestry biomass and wood chips production

The first stage of each life cycle system is the harvest of the wood from the forest by the forest owner. The wood resource may come from an established forest or a natural forest. In this paper, wood derives from either a natural forest which is located in the central-eastern part of The Netherlands or in British Columbia, Canada. Therefore no resources consumption is taken into account during tree cultivation. The forests in The Netherlands are mainly used for recreational purposes and, as a result production of timber is not their main goal. On the other hand, production of timber does take place in Canada.

In the first stage of this LCA, the wood is harvested, forwarded and finally chipped on site. In the case of Canadian wood pellets, the wood is harvested and forwarded as it will be transported to a lumber mill. The composition of fresh wood is taken from Phyllis2 database, where the wood is classified as forest wood (Energy research Centre of the Netherlands (ECN), 2013), and can be seen in Table 6. The fuel consumption and emissions produced regarding tree harvesting, forwarding and wood chip production depends on the equipment used. In this paper consumption data regarding the equipment was selected from the Wood Fuels Handbook published from European Biomass Association (Francescato et al., 2008). The harvester and forwarder machines have a productivity of approximately 15 solid m^3/h; whereas the chipper used is a high-power portable one with productivity of approximately 16 m^3/h.

Post the production of the wood chips; the chips are stored for approximately two weeks before they will be transported to the pretreatment plant for further processing.

Table 2
Life Cycle Inventory data.

	Value	Units	Reference
Harvest and storage			
Diesel	184	MJ/ton input	(Francescato et al., 2008)
Methane emissions	1.4	kg/ton input	(Wihersaari, 2005)
Nitrous oxide emissions	0.03	kg/ton input	(Wihersaari, 2005)
Pellet plant (NL)			(Hagberg et al., 2009; Mani, 2005; Sikkema et al., 2010; Nyboer, 2007)
Electricity	125	kWh/ton input	
Diesel	18	MJ/ton input	
Natural gas	1890	MJ/ton input	
Pellets	561	kg/ton input	
Pellet plant (CN)			(Magelli et al., 2009)
Electricity	62	kWh/ton input	
Diesel	114	MJ/ton input	
Natural gas	1760	MJ/ton input	
Pellets	555	kg/ton input	
Torrefaction plant (NL, CN)			(Uslu et al., 2008; Bergman et al., 2005)
Electricity	49.5	kWh/ton input	
Natural gas	1968	MJ/ton input	
Diesel	11.4	MJ/ton input	
Cooling water	6563	m^3/ton input	
Torrefied biomass	411	kg/ton input	
Biogenic CO$_2$ emissions	39	kg/ton input	
TOP plant (NL, CN)			(Uslu et al., 2008; Bergman et al., 2005)
Electricity	96	kWh/ton input	
Natural gas	1968	MJ/ton input	
Diesel	17	MJ/ton input	
Cooling water	6563	m^3/ton input	
Torrefied pellets	411	kg/ton input	
Biogenic CO$_2$ emissions	39	kg/ton input	
Coal mining and processing			(ART et al., 2010)
Electricity	25	kWh/ton output	
Water	180	kg/ton output	
Diesel	65.5	MJ/ton output	
Hard coal	35	MJ/ton output	
Transportation			(ART et al., 2010)
Truck lorry (>32 tons)			
Diesel	0.257	kg/vkm	
Barge ship			
Diesel	0.001	kg/tkm	
Freight train			
Electricity	0.04	kWh/tkm	
Diesel	0.002	kg/tkm	
Transoceanic freight ship			
Heavy fuel oil	0.003	kg/tkm	
Co-firing pellets (NL, CN)			(ART et al., 2010)
Coal	2931	kg/ton biomass input	
Ammonia	34.3	kg/ton biomass input	
Sulphuric acid	2.92	kg/ton biomass input	
Quicklime	7.3	kg/ton biomass input	
Limestone	47.4	kg/ton biomass input	
Chlorine	0.91	kg/ton biomass input	
Flue gases	22,858	Nm^3/ton biomass input	
Electricity	9001	kWh/ton biomass input	
Waste heat (air)	38,496	MJ/ton biomass input	
Waste heat (ocean)	10,112	MJ/ton biomass input	
CO$_2$ (fossil)	6320	kg/ton biomass input	
CO$_2$ (biogenic)	1552	kg/ton biomass input	
NO$_x$	2.02	kg/ton biomass input	
SO$_2$	4.57	kg/ton biomass input	
Particulate matter	0.46	kg/ton biomass input	
Ash	3992.6	kg/ton biomass input	
Gypsum	77.5	kg/ton biomass input	
Co-firing torrefied biomass or TOP (NL, CN)			(ART et al., 2010)
Coal	3.72	kg/ton biomass input	
Ammonia	43.65	kg/ton biomass input	
Sulphuric acid	3.76	kg/ton biomass input	
Quicklime	9.4	kg/ton biomass input	
Limestone	61.18	kg/ton biomass input	
Chlorine	1.1	kg/ton biomass input	
Flue gases	28,176	Nm^3/ton biomass input	
Electricity	11,449	kWh/ton biomass input	
Waste heat (air)	48,963	MJ/ton biomass input	
Waste heat (ocean)	12,861	MJ/ton biomass input	
CO$_2$ (fossil)	8038	kg/ton biomass input	
CO$_2$ (biogenic)	2050	kg/ton biomass input	
NO$_x$	2.57	kg/ton biomass input	
SO$_2$	5.63	kg/ton biomass input	
Particulate matter	0.56	kg/ton biomass input	
Ash	566	kg/ton biomass input	
Gypsum	100	kg/ton biomass input	

2.3.2. *Transportation*

The transportation stage takes place in three cases. The wood chips are transported to the pretreatment plant, the produced solid biofuel is transported to the power plant and the produced mixed ashes from the co-firing stage are transported to the cement factory. In Fig. 2 the locations of forest, pretreatment plants and power plant are presented. The Dutch wood chips are transported by truck lorry (>32 tons) to the pretreatment plants Then the upgraded biomass is transported to the power plant. Concerning Canadian biomass, the woody biomass is transported to the pretreatment plant by same type of lorry and then to Vancouver port by freight train. The pretreated biofuel is then transported to The Netherlands by ship, as presented in Fig. 3. Finally, the mixed ashes are transported to the cement production factory by barge ship. All transportation distances are presented in Table 3, with respect to The Netherlands, and Table 4, with respect to Canada. The data for all different kinds of transportation have been collected from the Ecoinvent database (ART et al., 2010), whereas, the distances themselves have been calculated using Google maps (Google, 2014) and websites specialised on transport (SeaRates LP, 2014).

2.3.3. *Production of solid biofuel*

Three different solid biofuels are produced from the wood chips or sawdust; pellets, torrefied biomass or torrefied pellets. Electricity, natural gas and diesel are consumed in the Dutch pellet plant for the different steps of the pelletisation technology. Data regarding energy consumption of each fuel per functional unit in the pellets plants can be seen in Table 5. In addition, the steps during pelletisation are presented in Fig. 4. With respect to dry matter, the input is the same as the output of the technology; the only variable changing in terms of composition is the moisture content of biomass. The composition of the produced wood pellets can be seen in Table 6. Data regarding wood pelletisation and Canadian lumber mills on a process level have collected from international literature (Hagberg et al., 2009; Mani, 2005; Sikkema et al., 2010; Nyboer, 2007). It was decided not to use Ecoinvent database because, even though it included a process regarding wood pelletisation; it was evaluated high with respect to electricity consumption and its input was industrial wood residue.

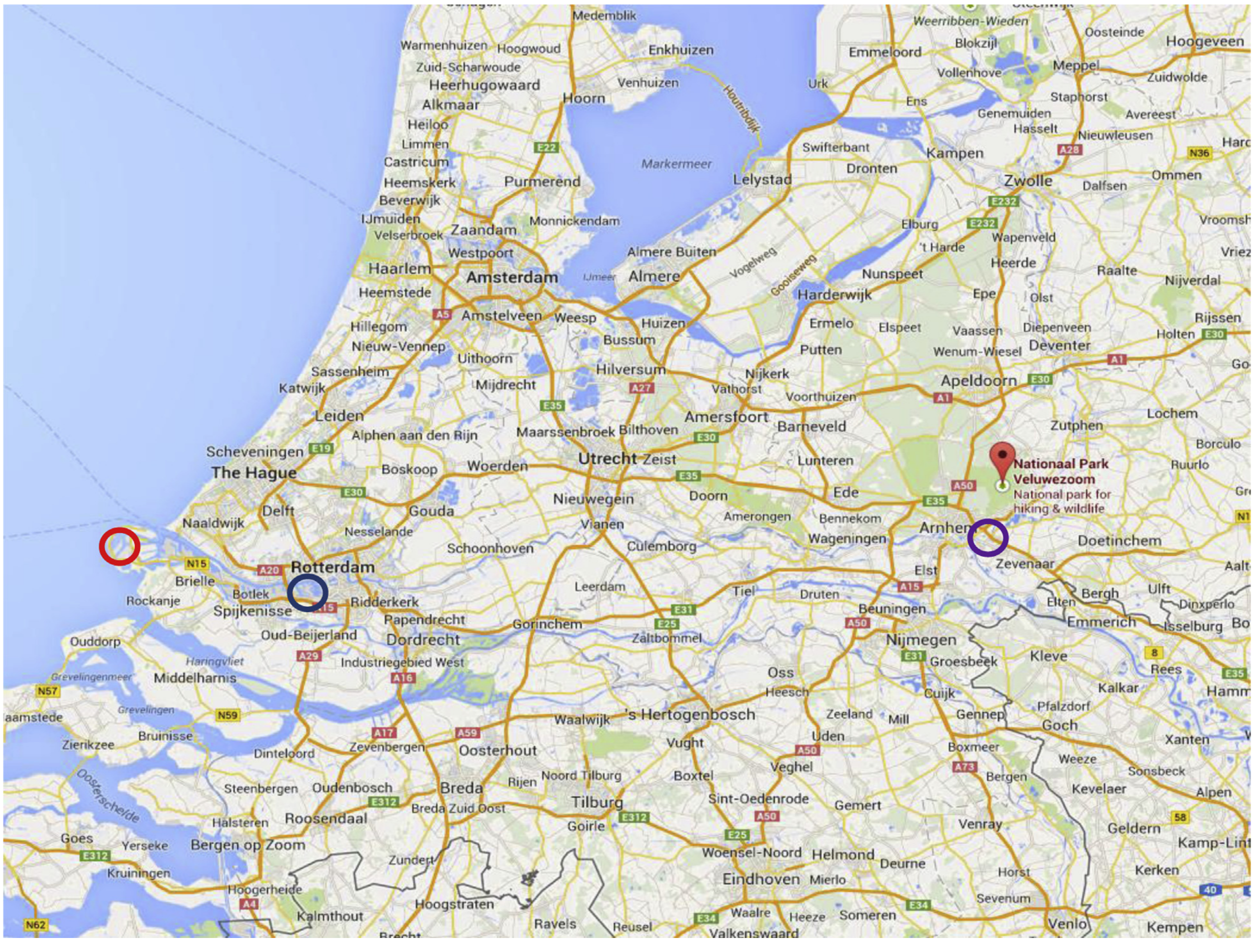

Fig. 2. Plants and forest locations; red: power plant, blue: pellet plant, purple: torrefaction and TOP plant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In torrefaction of woody biomass the energy efficiency of the process is 90% and the mass efficiency is 70%. That said, 90% of the feedstock's energy and 70% of the feedstock's mass are transferred to the main solid product. In torrefaction technology part of the heat needed for drying, to approximately 15% moisture content on a wet fuel basis, is produced through combusting all the produced torrefaction gas. The rest of needed heat is produced through natural gas combustion in a boiler with an efficiency of 90%, as presented in Fig. 4. The energy consumption is presented in Table 5. However, since the torrefaction gas has biomass feedstock as its source, the produced CO_2 is biogenic and, therefore, not considered a GHG. The composition of the produced torrefied wood is

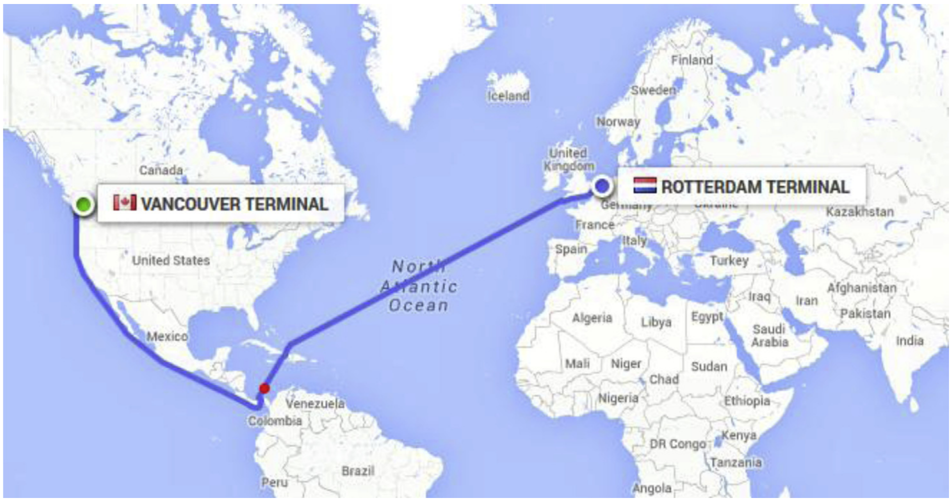

Fig. 3. Wood pellet transportation by ship to The Netherlands.

Table 3
Transportation distances for Dutch biomass (all distances in km).

	From forest to pretreatment plant (truck)	From pretreatment plant to power plant (barge ship)	From power plant to cement factory (barge ship)
Pellets (NL)	130	60	20
Torrefied biomass (NL)	35	100	20
TOP (NL)	35	100	20

presented in Table 6. Data on the process level have been collected mainly from research conducted by ECN (Bergman et al., 2005; Uslu et al., 2008). ECN has developed and upgraded their torrefaction technology regarding wood and it has published several reports based on carried out experiments.

Finally, in the torrefaction followed by pelletisation (TOP) method the steps are a combination of torrefaction and pelletisation pretreatment processes. Therefore, the details for this pretreatment technology are similar when compared to those two pretreatment processes, and are presented in Fig. 4. However, the power needed for size reduction and densification of torrefied biomass is 70–90% (Bergman et al., 2005) and 70% (Uslu et al., 2008) less than in pelletisation of non-torrefied biomass, respectively. TOP's energy consumption is presented in Table 5. The composition of produced TOP woody biomass in this scenario can be seen in Table 6. Similar to wood torrefaction ECN has conducted several reported experiments regarding TOP process (Bergman et al., 2005).

It should be pointed out that the electricity which is consumed during the pretreatment stages has different sources. Data regarding Dutch electricity mix was collected from Ecoinvent database, whereas data for Canadian electricity mix was collected from literature (IEA, 2000). Dutch electricity mix is based on fossil fuels, especially natural gas; whereas Canadian electricity mix employs more hydropower.

2.3.4. Coal supply chain

Data from the coal supply chain have been collected from Ecoinvent database. The data used were specifically for coal utilised in the Dutch electricity production content. The coal burned in power plants is mainly imported and extracted in underground mines all over the world. Most of the coal utilised in Dutch power plants is delivered from South Africa, Latin America, North America and Australia.

2.3.5. Co-firing of solid biofuel with coal

Co-firing is the actual stage where electricity will be generated. The net electrical efficiency of the power plant was selected to be 40%. That said, the consumption of energy regarding operation of machineries is included in the efficiency. Additionally, during electricity generation there is also production of gypsum and mixed ashes. The former can be sold by an electricity company as synthetic gypsum, whereas regarding the latter an electricity company would need to pay for its disposal. Therefore, it is given to a cement production company for free. As a result, this stage consists of a multifunctional process. On the other hand, data regarding materials consumption, such as limestone, quicklime, ammonia and sulphuric acid have been acquired from Ecoinvent database. However, the amounts of sulphur dioxide that are emitted have been based on Dutch emission limits imposed by the Dutch Ministry of Infrastructure and Environment; 200 mg/Nm^3 flue gas (InfoMil, 2010). The emission limits for nitrogen oxides have been based on the specific technology used by Dutch power companies; 25 g/GJ$_{\text{input}}$ (Robesin et al., 2009). Concerning dust emissions, the limits have been proposed via directives reported in the Official Journal of the European Union (European Union, 2008). The same limits are applied to The Netherlands and are 25 and 50 mg/Nm^3 flue gas for PM2.5 and PM10, respectively. The emission limits are given in Table 7.

All data collected and used in this paper have been acquired from international literature or Ecoinvent database version 2. The various sources of the data are presented in Table 8.

Table 5
Energy consumption per functional unit during pretreatment.

	Pelletisation (NL)	Torrefaction (NL, CN)	TOP (NL, CN)	Pelletisation (CN)
Electricity (kWh$_e$/kWh$_e$)	0.024	0.010	0.019	0.012
Natural gas (MJ/kWh$_e$)	0.37	0.414	0.414	0.348
Diesel (MJ/kWh$_e$)	0.004	0.002	0.004	0.023

3. Results

This paper assumes that part of the coal will be substituted with pretreated biomass and undergo co-firing to generate power. Table 9 shows the absolute characterised impacts of each co-firing chain in order to evaluate them. Furthermore, this section presents the normalised results, with the reference case, in order to point out the possible impact reduction benefits of each co-firing chains. The normalised results are presented in Figs. 5–7. Due to simplification reasons the Dutch co-firing chains are abbreviated as NL, whereas the Canadian ones as CN in the graphs and tables.

3.1. Global warming potential

The biggest decrease in global warming potential is achieved when Dutch torrefied biomass is co-fired as presented in Fig. 3; the decrease is approximately 12%. The rest of the co-firing chains present a decrease of approximately 11%. However, if the produced biogenic CO$_2$ will be taken into account, then the pelletisation system results in the lowest GWP among three pretreatment methods. The difference is between 7 and 9%, with Dutch pellets showing the lowest increase and Canadian TOP biomass showing the largest increase. Furthermore, when Canadian biomass is pretreated and imported to The Netherlands, the increase of the GWP is approximately 0.5–1% higher than Dutch biomass cases. With

Table 4
Transportation distances for Canadian biomass (all distances in km).

	From forest to pretreatment plant (truck)	From pretreatment plant to Vancouver port (train)	From Vancouver port to Rotterdam port (freight ship)	From Rotterdam port to power plant (barge ship)	From power plant to cement factory (barge ship)
Pellets (CN)	140[a]	750	18,600	25	20
Torrefied biomass (CN)	575	695	18,600	25	20
TOP (CN)	575	695	18,600	25	20

[a] combination of distances between forest and lumber mill, and lumber mill and pellet plant.

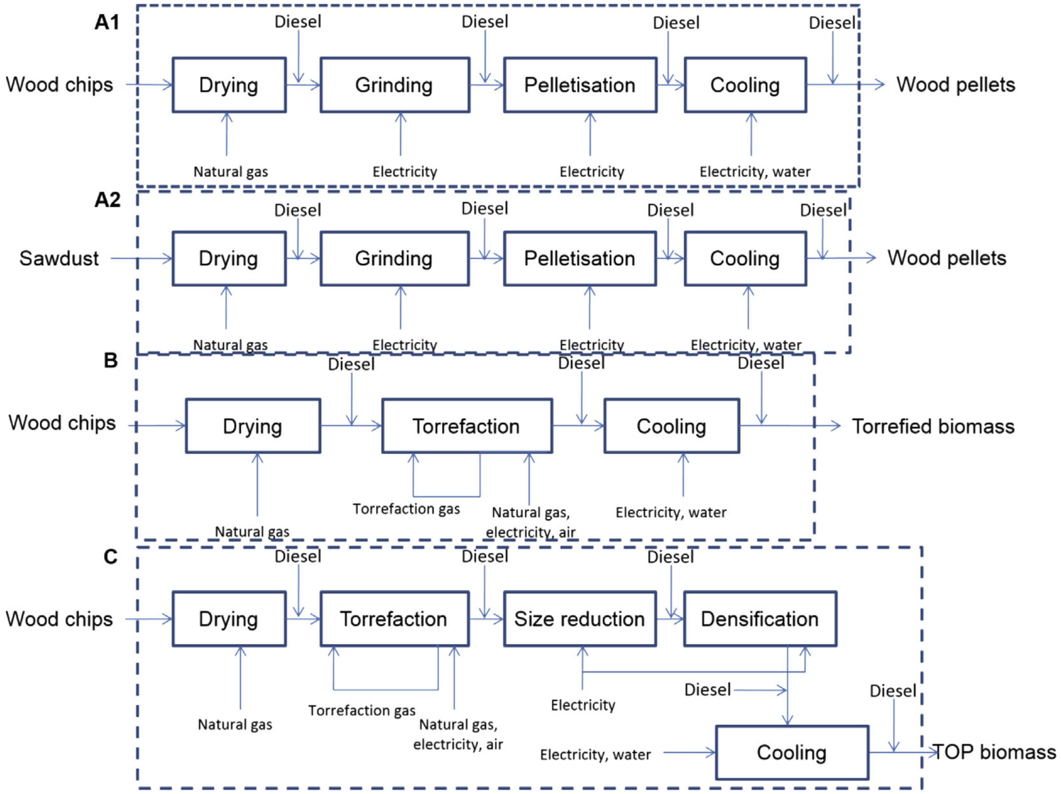

Fig. 4. Steps in the pretreatment processes, A: pelletisation; B: torrefaction; C: TOP.

respect to global warming the co-firing stage is dominating the total score in each case. Additionally, transport and pretreatment stages are contributing as much as 7% in total.

In all cases the most significant fossil gas emitted contributing to global warming score is CO_2, whereas most of it is produced during the co-firing stage. Next to it, methane is the second largest contributor, approximately 3% of the fossil gases emitted. Most of the methane is emitted during the production of hard coal.

3.2. *Acidification potential*

Regarding the acidification, Dutch torrefied biomass and torrefied pellets show an improvement of approximately 7%, when compared to the reference case as presented in Fig. 4. Furthermore, Dutch pellets also show an improvement of 6%. On the other hand, Canadian biomass results in higher scores because the transportation stage is the one that dominates the acidification potential. This increase can be up to 30% as in the case of Canadian pellets. However, in torrefaction and TOP this increase is approximately 12%; still fair enough. Apart from transportation stage, co-firing also contributes significantly, 41% in average. Whereas, mining and processing of coal, pretreatment and harvesting of biomass stages only contribute slightly.

With respect to acidification sulphur dioxide and nitrogen oxides are the main contributors of approximately up to 56% and 40%, respectively. For both emissions transportation by ship is the stage where they are mostly produced.

Table 6
Composition of solid fuels.

	Woody biomass	Wood pellets	Torrefied biomass	TOP
Moisture % (a.r.)	48.90	10.00	3.00	3.00
Ash % (a.r.)	0.50	0.90	1.20	1.20
Hydrogen % (a.r.)	3.00	5.25	5.06	5.06
Carbon % (a.r.)	24.80	43.60	57.64	57.64
Nitrogen % (a.r.)	0.01	0.02	0.03	0.03
Sulphur % (a.r.)	0.01	0.02	0.02	0.02
Oxygen % (a.r.)	22.75	40.20	33.02	33.02
LHV MJ/kg (a.r.)[a]	7.85	15.71	20.46	20.46

[a] the fuels calorific values have been determined with the Milne's empirical formula.

Table 7
Emission limits of a co-firing power plant.

NO_x (g/GJ_{input})	PM < 2.5 (mg/Nm^3 flue gas)	PM < 10 (mg/Nm^3 flue gas)	SO_2 (mg/Nm^3 flue gas)
25	25	50	200

Table 8
Data references.

Stage-processes	Source of reference
Harvesting	(Francescato et al., 2008)
Storage	(Wihersaari, 2005)
Torrefaction	(Bergman et al., 2005; Uslu et al., 2008)
Torrefaction and pelletisation	(Bergman et al., 2005; Uslu et al., 2008)
Pelletisation	(Hagberg et al., 2009; Mani, 2005; Sikkema et al., 2010; Nyboer, 2007)
Coal mining and processing	(ART et al., 2010)
Transportation	(ART et al., 2010)
Equipment used[a]	(ART et al., 2010)

[a] Except equipment used for harvesting.

Table 9
CML and Traci characterized impacts, using economic allocation.

	GWP (kg CO_2 eq./kWh_e)	Acidification potential (kg SO_2 eq./kWh_e)	Photochemical oxidation potential (kg C_2H_4 eq./kWh_e)
Pelletisation (NL)	0.811	0.0881	$8.64*10^{-4}$
Torrefaction (NL)	0.808	0.0869	$8.61*10^{-4}$
TOP (NL)	0.814	0.0874	$8.68**10^{-4}$
Pelletisation (CN)	0.82	0.121	$1.39**10^{-3}$
Torrefaction (CN)	0.816	0.105	$1.08**10^{-3}$
TOP (CN)	0.818	0.105	$1.09**10^{-3}$
Coal mix (ref. case)	0.914	0.0934	$9.04*10^{-4}$

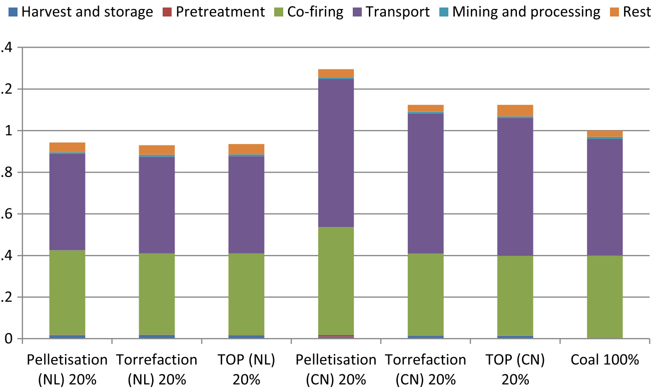

Fig. 6. Normalised results on acidification potential (1 = 0.0934 kg SO_2 eq./kWh_e).

3.3. Photochemical oxidation potential

Finally, photochemical oxidation potential is only improved when Dutch woody biomass is co-fired. The reduction is between 4 and 5%; with torrefied biomass showing the highest decrease. On the other hand, the Dutch TOP biomass results in the lowest reduction, whereas, Dutch pellets result is between. The Canadian co-firing chains are worse than the reference case, especially Canadian pellets result in the worst score. Furthermore, the scores of Canadian biomass can be up to 53%, for pellets, or approximately 20%, in the cases of torrefied biomass and torrefied pellets. As presented in Fig. 5 transportation stage has the highest contribution, 60% for Dutch co-firing chains and 85% for Canadian cases, in average. On the other hand, mining and processing of coal and harvesting of biomass have a low contribution in the total score, 2% in average.

With respect to photochemical oxidation the nitrogen oxides are the only dominant factor for this environmental impact. Their contribution is up to 99% for both domestic and Canadian biomass, and they are mainly derived from transportation stage, more specifically transport by ship, and co-firing stage.

4. Discussion

Even if coal is replaced on a 20% energy input basis, the achieved emissions reduction is not as high. Harvesting, storing and pretreating biomass in order to co-fire it, contribute to all three environmental impacts, especially global warming. Furthermore, the decrease in combustion efficiency, when biomass is co-fired with coal, should be taken into account for emissions reduction. The harvest and storage, and pretreatment stages of biomass do not result in environmental benefits when compared with mining and processing of coal, if the same quantities of biomass and coal are compared. Co-firing, transportation and harvest and storage stages have the highest contribution among all stages. Therefore, focussing on reducing the impacts of these stages will have the highest influence on the score and, subsequently, the biggest environmental benefit. Regarding the co-firing stage, improving the co-combustion power generation efficiency will noticeably improve global warming impact. Therefore, co-firing biomass which is more coal-alike will help with this matter. Alternatively, making use of fuels from closer sources or using means of transportation which are more environmental friendly will also improve the impacts of the biomass co-firing chains. With respect to The Netherlands coal can be supplied from other European countries. That said, both acidification and photochemical oxidation potentials would be significantly improved. Harvest and pretreatment stages of biomass, even though they consume high amounts of energy, show a small contribution to the selected impacts, such as global warming and photochemical oxidation. Among the pretreatment processes, torrefaction and TOP processes have the highest prospects to be improved from an energy point of view in the near future, as they are relatively new technologies when compared with pelletisation. Torrefaction is a novel technology, it can be improved further, become less energy consuming and improve the grindability and combustion characteristics of the solid fuel produced.

The fact that the substitution of coal is done on an energy input basis and the fact that all three solid biofuels have a lower heating value than coal, results in higher mass requirements of solid biofuels. That said, if the substitution would be done on a mass basis, then torrefaction would appear more attractive for a final choice. Using coal and biomass from a closer source will benefit acidification and photochemical oxidation impacts. Furthermore, torrefied biomass and TOP are more coal-alike; therefore, they should result

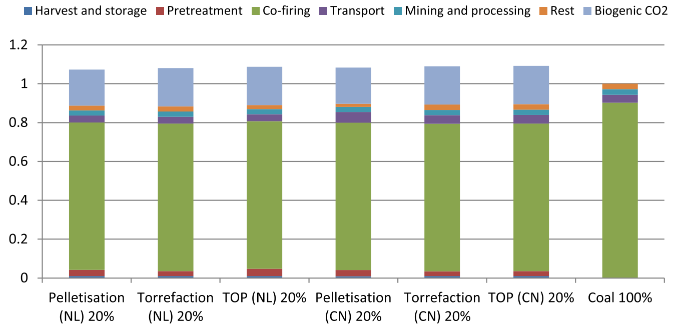

Fig. 5. Normalised results on global warming potential (1 = 0.914 kg CO_2 eq./kWh_e).

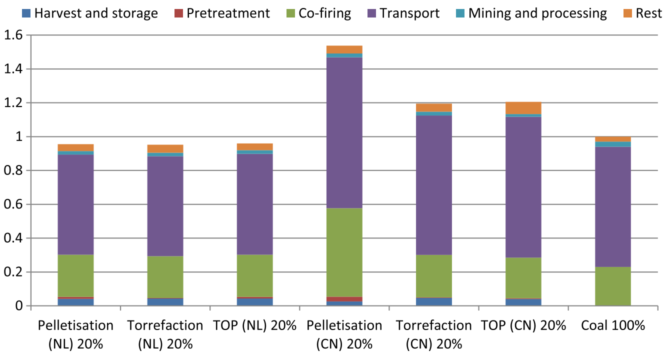

Fig. 7. Normalised results on photochemical oxidation potential (1 = $9.04*10^{-4}$ kg C_2H_4 eq./kWh_e).

in higher combustion efficiency than conventional wood pellets, but this is not taken into account in this paper.

The comparative increase of photochemical oxidation and acidification impacts of the pellet co-firing systems is very high when it is compared with the increase between torrefied and TOP systems. This increase is mainly due to the fact that the heating value of wood pellets is lower than torrefied biomass and TOP. This results in bigger quantities of pellets to be transported from Canada to The Netherlands than the other two kinds of pretreated biomass. Moreover, the additional processing of fresh biomass upstream the pelletisation stage is slightly contributing to the impacts score.

In this paper, it was assumed that only fresh biomass will be stored and no storage will take place post the processing of fresh biomass. However, if pretreated biomass is to be stored in the pretreatment plant or in the power plant, then the pelletisation systems will result in worse scores in global warming and photochemical oxidation impacts. This will happen because, with respect to biomass processed with torrefaction technology, pellets will continue degrading faster and, subsequently, emitting more methane and N_2O.

The positive effects in global warming, when pretreated biomass replaces coal, are lower than in other analyses mentioned below. The maximum reduction is approximately 12%, when compared to the reference coal system. However, in this paper the avoided emissions were not taken into account when the biomass, will be left to the field to decompose or the not-emitted fossil CO_2 emissions, due to coal replacement. This kind of decisions have resulted in negative GHG emissions during the LCI step of previous studies (Damen and Faaij, 2003; Tabata et al., 2011; Mann and Spath, 2001). Furthermore, sometimes researchers do not include storage emissions of biomass, even though it will degrade if it is not utilised in a short period of time. Moreover, the kinds of pretreatment technologies that were taken into consideration are quite energy consuming, and finally, the source of biomass is not derived from waste streams. The latter would improve considerably the impact scores, as most of the emissions due to the stages prior to pretreatment stage would decrease significantly. Finally, in this paper allocation occurs in the co-firing or coal combustion stage. As a result, part of this stage's emissions is allocated for the production of 1 kWh_e, and therefore, the scores are smaller. Thus, the global warming score of the reference case is 0.914 kg CO_2 eq./kWh_e, whereas normally it should be closer to 1 kg CO_2 eq./kWh_e.

Huang et al. (2013) performed a similar study of torrefied biomass, but with rice straw as the biomass source. They present results of lower reduction of the global warming potential with respect to their reference case, approximately 8.7%. This can be explained with the different biomass kind that is used in their study, with the fact that rice straw has a higher content on nitrogen and sulphur, and because they included an increase of GHG emissions of farmland due to the straw removal. The latter was not considered in this paper. Fan et al. (2011) performed a study where pyrolysis bio-oil (from several biomass sources) replaces coal in a power plant for electricity generation. Their results with respect to GWP are in alignment with the results of torrefied biomass in this study. The decrease is about 12% when compared with their reference system. Royo et al. (2012) conducted an LCA study regarding Spanish forest residual biomass co-firing with coal on 10% on energy input basis. They found out that the GHG emissions were decreased by approximately 7% when biomass replaced coal, when compared to their reference system. Because the biofuel in their case is not pretreated at all, their results are slightly higher than in this paper, but still in alignment with the results of this study regarding global warming potential. Finally, Hartmann and Kaltschmitt (1999) performed an LCA study of straw and wood co-firing with coal on a 10% on energy input basis. The authors did not consider changing the net electrical efficiency of the plant due to co-firing, nor considered pretreatment of the biomass. Their results are close to the results of this paper, approximately 6.3% decrease in GHG emissions, when compared to their reference case.

5. Conclusions

It is very likely that biomass co-firing with coal in Dutch power plants will become mandatory during the next years. Furthermore, the current trend is direct co-firing of wood pellets with coal. However, there are novel pretreatment technologies developed which may improve co-firing from an energy perspective and also improve the biomass logistics. That said torrefaction and, especially TOP can be such technologies. The results obtained in this LCA paper show that co-firing and transportation stages contribute the most regarding all three environmental impacts overall.

In this paper Life Cycle Assessment (LCA) is used to evaluate the environmental benefits on global warming, acidification and photochemical oxidation potentials, of biomass direct co-firing with coal on a 20% energy input basis, when compared with coal-fired power generation in The Netherlands. The solid biofuel is produced from Dutch or Canadian forestry biomass via pelletisation, torrefaction or torrefaction and pelletisation. The results show that co-firing and transportation stages contribute the most regarding all three environmental impacts overall. The results also show that torrefied biomass co-firing chain can be considered the best option when Dutch biomass is utilised. The reduction is approximately 12% for global warming, 7% for acidification and 5% concerning photochemical oxidation potentials. Even when biomass is imported from Canada, this also results in substantial reduction regarding global warming potential, when compared to the reference case. Alternatively, co-firing of domestic biomass results in a better performance than Canadian biomass for all three impact categories. If TOP further improves in the future or considers that TOP biomass has a higher co-firing efficiency than wood pellets, then TOP co-firing chain is more beneficial than wood pellets co-firing chain. Therefore, the Dutch government and power companies might consider biomass pretreated with torrefaction as a mean of achieving environmental goals.

Further areas of investigation could include an evaluation regarding emission reduction practices in different Dutch power plants, as well as the utilisation of all Dutch forestry biomass from forest maintenance and possible replacement of coal with it.

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